(12) UK Patent Application (19) GB (11) 2 238 880 (13) A

(43) Date of A publication 12.06.1991

(21) Application No 8927582.0

(22) Date of filing 06.12.1989

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(51) INT CL^5
G02B 7/18 7/185

(52) UK CL (Edition K)
G2J JMH
G2F FCH F23E F25G F25R F26R

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(58) Field of search
UK CL (Edition J) G2F FCH, G2J JMH
INT CL^4 G02B, G02F
Online databases: WPI

(54) Optical correction apparatus

(57) An optical correction apparatus comprising, in combination, a light-modulatable deformable mirror comprising a photoconductive layer (5) having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer (4), a light-reflective layer (2) overlying the piezoelectric layer, and means (3 and 6) for applying an electric field across the photoconductive and piezoelectric layers, and projection means (30 - 36 Figure 3, not shown) for applying to the first surface thereof a light pattern adapted to produce the desired deformation of the mirror.

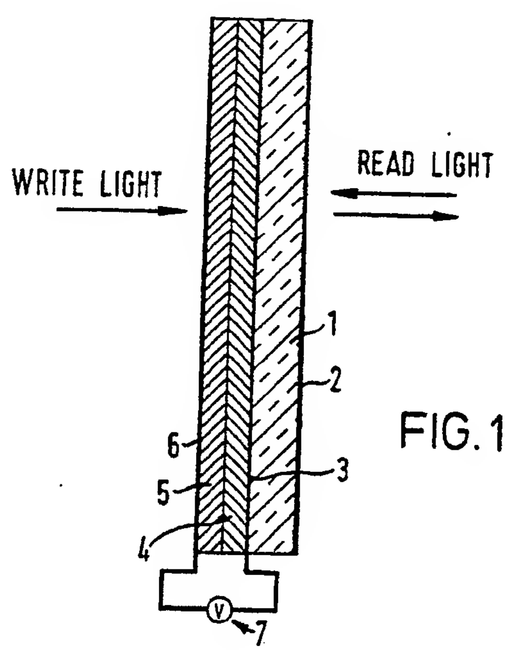

FIG. 1

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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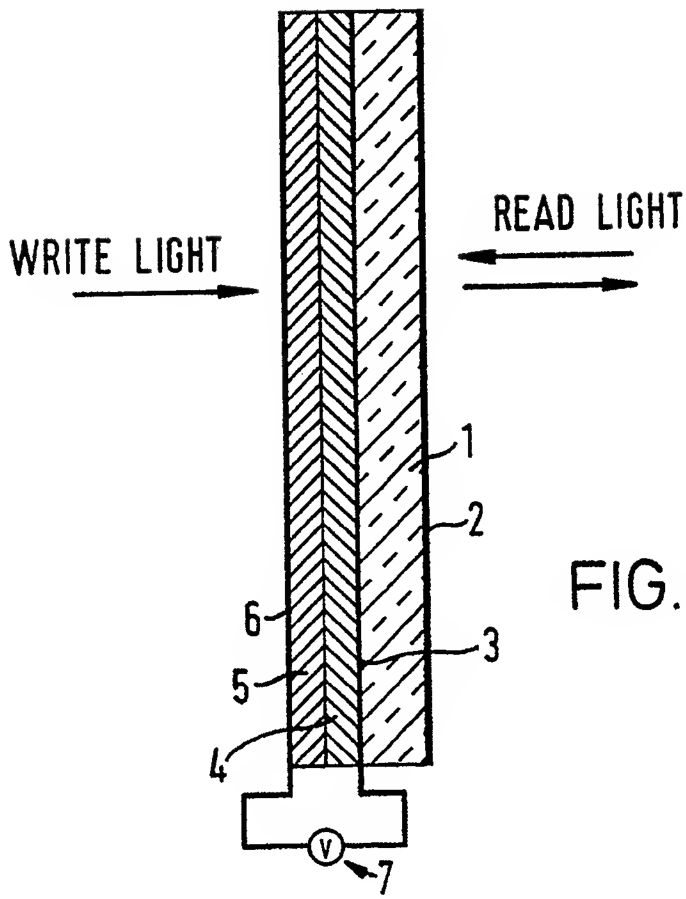


FIG. 1

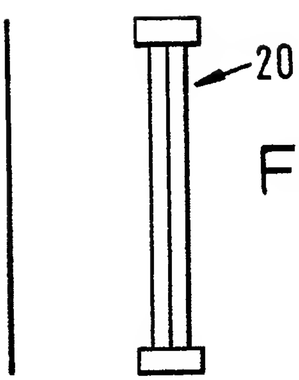


FIG. 2a

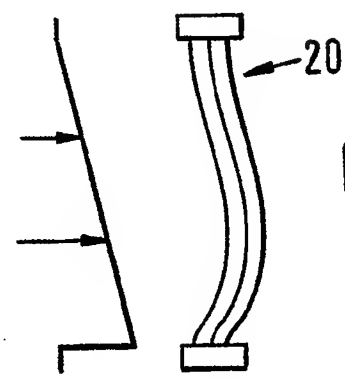


FIG. 2c

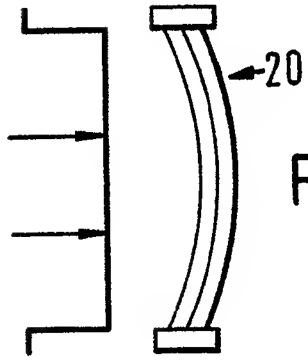


FIG. 2b

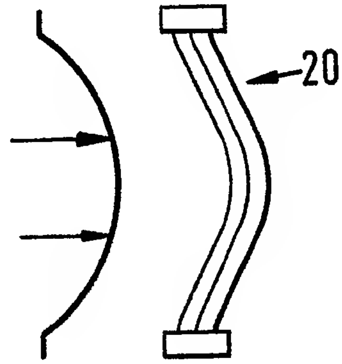
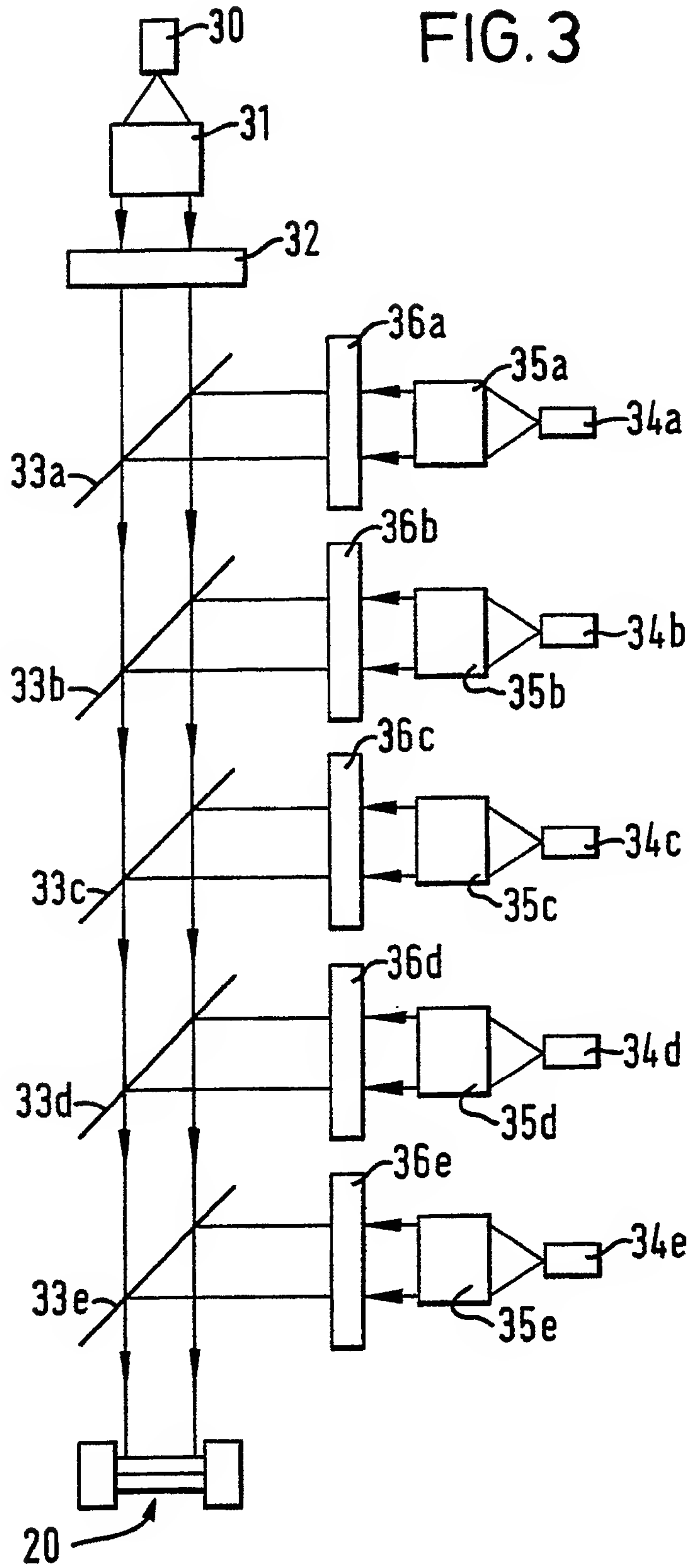


FIG. 2d

FIG. 3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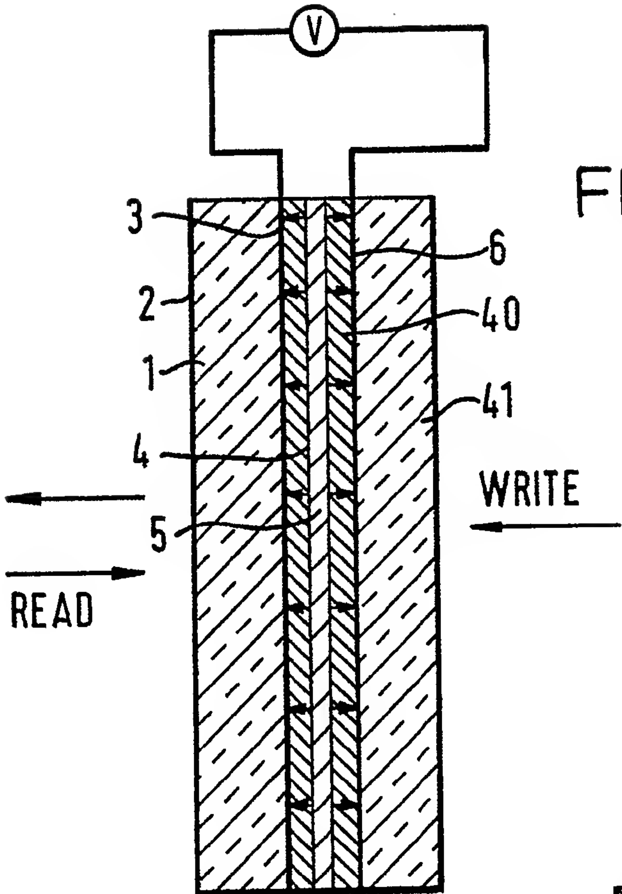

FIG. 4

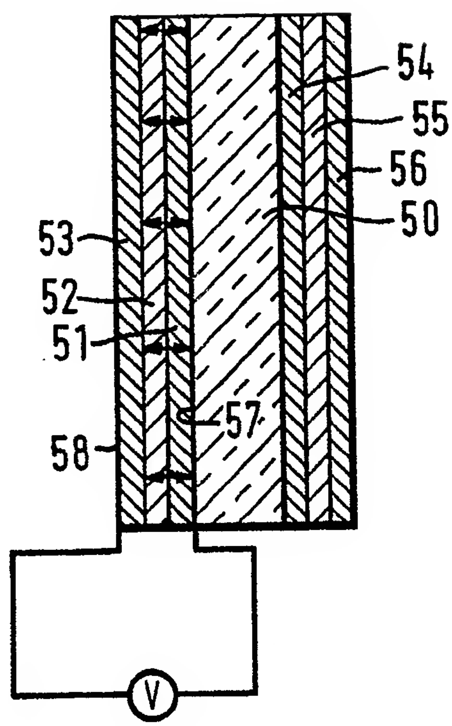

FIG.5

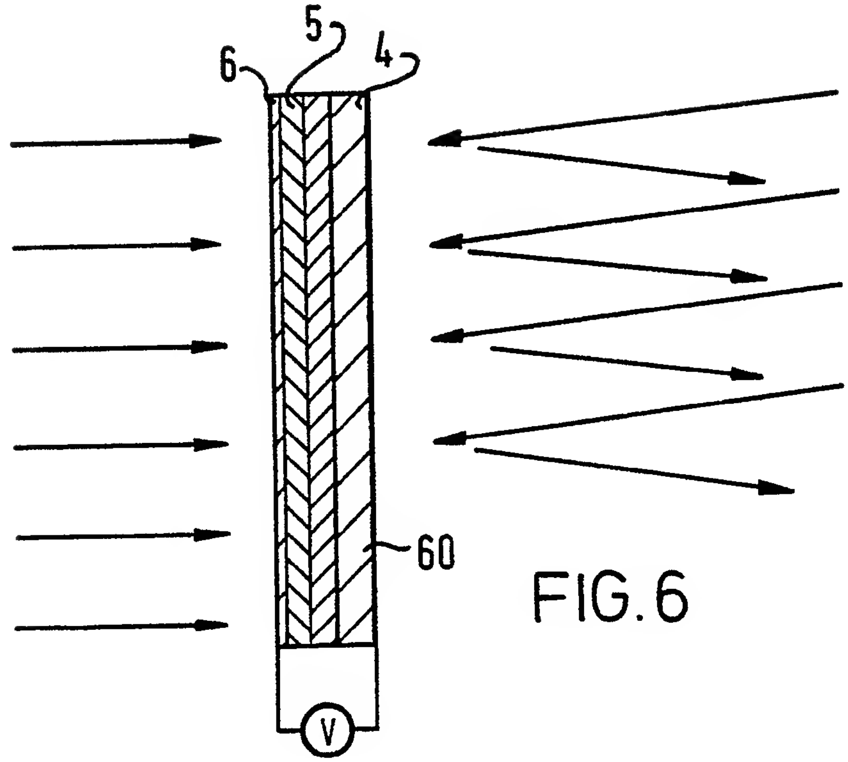

FIG. 6

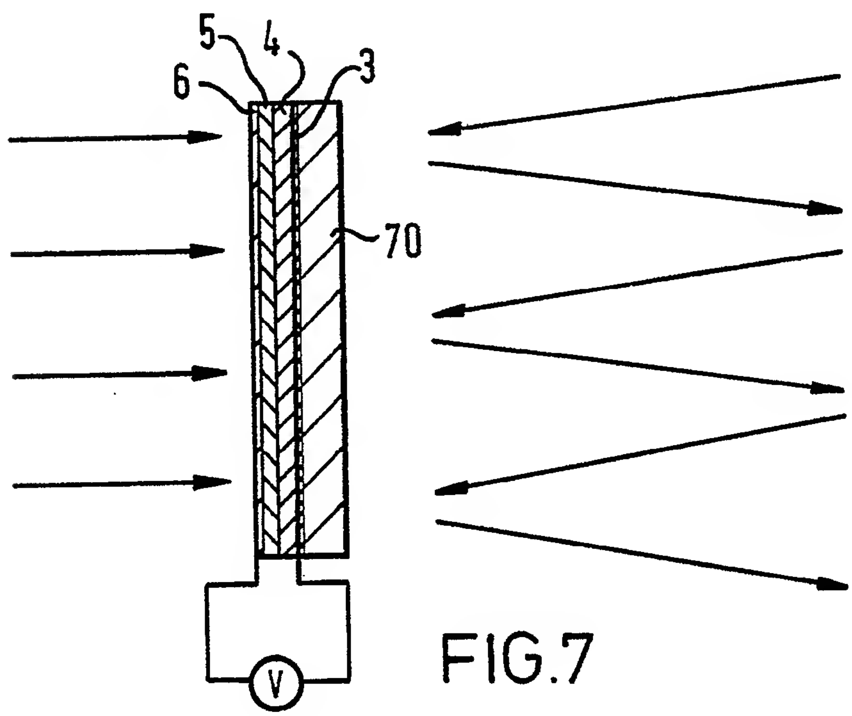

FIG. 7

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OPTICAL CORRECTION APPARATUS

This invention relates to an optical correction apparatus including a light-modulatable deformable mirror, to an optical system incorporating such optical correction apparatus, and to a light-modulatable deformable mirror suitable for use in such apparatus.

Deformable mirrors can be used to correct for aberrations in an optical system, such as spherical and coma aberrations. Known deformable mirrors make use of an array of piezoelectric actuators in contact with a deformable metal surface. Typically 15 to 30 actuators are used, each controlled using a servo loop with individual adjustment to optimise the correction achieved. The control of the device to achieve the desired correction is therefore complex.

The present invention provides an optical correction apparatus comprising, in combination,

(a) a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, and

(b) projection means for applying to the first surface thereof a light pattern adapted to produce the desired deformation of the mirror.

With the mirror of the invention, a suitable pattern of light may be projected on to the first surface of the photoconductive layer to achieve the configuration of the reflective surface which will give the desired correction. Correction for several different types of aberration may be achieved by selection of a suitable pattern or combination of patterns. The controlling light patterns need not correct for any specific aberration themselves. Each pattern could correct for increasingly higher orders of phase aberration. Thus, uniform light corrects for quadratic phase error, linearly varying intensity corrects for cubic phase errors and quadratic variation of intensity corrects for quartic phase error. Combining such light patterns may provide a much more versatile and useful addressing method than using a combination of specific patterns that correct for specific aberrations.

In one preferred embodiment of the invention the mirror incorporates a thin but fairly rigid substrate on which the active elements are formed. This is preferably a thin glass element. As well as aiding device construction and the attainment of a high quality mirror surface, this layer, although electrically inactive, makes a major contribution to the mechanical properties and hence the mirror deformation. It is the presence of the thin glass substrate that provides an overall curvature of the mirror but limits the maximum spatial frequency achievable to many times the

substrate thickness, e.g. ≈1 mm. It is therefore well suited to electronic focussing and aberration correction in optical systems.

An alternative preferred structure utilises just the photoconductor, piezoelectric and associated layers stretched over an aperture in a 'drum skin' configuration. The layered structure is very flexible and its flat shape is maintained by tension. Applying uniform illumination in this case will change the strain in the layers but will not result in an overall curvature. This structure does not provide for low spatial modulation frequencies and has a maximum response for light illumination areas which are a few times the film thickness in size, e.g. 100 μm to 1 mm region.

For efficient operation, the bias voltage must be transferred between the two layers (i.e. photoconductor and piezoelectric layers) when the write illumination changes. Preferably, therefore, the resistance per unit area of the photoconductor should change from 10 times to 1/10 of that of the piezoelectric layer as the write signal goes from light to dark.

Preferably, the projection means comprise a light source and a mask between the light source and the first surface. An especially preferred apparatus includes at least one, more preferably a plurality of, additional projection means having a different mask, and combining means for combining

the output from all the projection means. Means may be provided for individually controlling the intensity of the light emitted by each projection means. The light source in the or each projection means may be a laser diode, permitting precise control to be achieved by varying the voltage on the diodes. In certain circumstances, it may be possible to control the voltages in accordance with a feedback loop measuring, for example, the intensity of light reflected by the optical system of which the apparatus forms a part.

The invention also provides an optical system, including an optical correction apparatus according to the invention, and means for measuring a characteristic of the light passing through the optical system and for controlling the output of the projection means in accordance therewith.

Using the apparatus of the invention, it may be possible to use in some circumstances optical systems which provide a relatively low inherent correction of optical errors, and which are therefore cheaper than systems providing full correction, and to incorporate an apparatus in accordance with the invention to provide active correction.

The invention also provides a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezo-electric layer, a light-reflective layer overlying the piezoelectric layer, means for applying an electric field

across the photoconductive and piezoelectric layers, a glass support between the piezoelectric layer and the reflective layer, a second piezoelectric layer located on the first surface of the photoconductive layer, and a second glass support located on the second piezoelectric layer, the two piezoelectric layers being such that, under the action of an applied electric field, one piezoelectric layer expands while the other contracts.

Another aspect of the invention provides a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, wherein a glass support is provided between the piezoelectric layer and the reflective layer, and a second piezoelectric layer located on the first piezoelectric layer, the layers having their molecules aligned substantially in opposite directions, wherein the opposite face of the glass support is provided with two piezoelectric layers, whose molecules are substantially unaligned, and an overlying photoconductive layer.

Yet another aspect of the invention provides a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a

modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, means for applying an electric field across the photoconductive and piezoelectric layers, and rigid mounting means holding the periphery of the layers such that the layers are supported solely thereby.

A still further aspect of the invention provides a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a polymeric piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, wherein the light-reflective layer is a layer of the same material as the piezoelectric layer and serves as a substrate for the layers.

The invention further provides a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, wherein the light-reflective layer is a metal layer serving as a substrate for the mirror.

Reference is made to the drawings, in which:

Figure 1 is a diagrammatic sectional view through a deformable mirror for use in an optical correction apparatus according to one preferred embodiment of the invention;

Figures 2a to 2d are diagrams illustrating the response of the mirror shown in Figure 1 to different write light functions;

Figure 3 is a diagram illustrating an optical correction apparatus according to one embodiment of the invention; and

Figures 4 to 7 are diagrammatical sectional views of deformable mirrors according to alternative embodiments of the invention.

Referring first to Figure 1, the deformable mirror comprises a glass substrate 1 approximately 100 μm thick having an aluminium reflective layer 2 on one surface thereof. On the other surface of the glass 1 is an aluminium layer 3 serving as an electrode. A thin (9μm) layer 4 of a piezoelectric material, suitably poly(vinylidene fluoride) (PVDF), is in contact with the electrode 3, and this is followed by a layer 5 of a photoconductive material, suitably poly(vinyl carbazole) doped with 5% trinitro fluorenone. A semitransparent film 6 of gold is evaporated on to the photoconductor to form a second electrode. Electrical connections are made to the electrodes 3 and 6 and to a voltage source 7.

Figures 2a to 2d show the effect of applying different write light functions to the photoconductor. In Figure 2a, no illumination is applied to the deformable mirror 20 and no optical correction is produced. In Figure 2b, the illumination is uniform, producing correction of quadratic phase error. If the illumination varies linearly in intensity across the photoconductor, as shown in Figure 2c, the resultant change in shape of the mirror 20 is such as to provide correction of cubic phase error, while quadratic variation of the illumination, as in Figure 2d, produces a shape which gives correction of quartic phase error.

Figure 3 shows a possible optical arrangement for projecting write light functions on to the deformable mirror 20. A laser diode 30 serves as the write light source. The laser light passes through collimating optics 31 and through a uniform mask 32 which serves to control the intensity of the uniform beam which corrects for quadratic phase errors. The beam passes through five dielectric beam splitters 33a to 33e with optimised transmission/reflection ratios, and then falls on the photoconductive layer of the mirror 20. Associated with each of the beam splitters 33 is a separate laser diode 34 with collimating optics 35 and an appropriate mask 36 giving a predetermined correction pattern. Thus, the first mask 36a gives a positive linear variation in the X axis, the second 36b gives a negative linear variation in the X axis, the third and fourth 36c and 36d give respectively

positive and negative linear variation in intensity in the Y axis, and the fifth 36e gives a quadratic variation in intensity. The separate beams with their different intensity patterns are mixed together by the beam splitters 33, so that the resultant modulating beam falling on the photoconductor of the mirror 20 gives rise to a mirror shape which provides correction for quadratic, cubic and quartic phase errors at levels determined just by the DC drive currents applied to the laser diodes 34.

The standard structure employing a sandwich of glass and PVDF is limited to operation in a temperature-controlled environment because of the differences in thermal expansion coefficients (PVDF $\approx 11 \times 10^{-5}$, Glass $\approx 5.5 \times 10^{-7}$). To permit use other than in a temperature-controlled environment, structures such as those shown in Figures 4 and 5 may be used. The structure shown in Figure 4 adds to that shown in Figure 1 a second piezoelectric layer 40 between the photoconductor layer 5 and the gold electrode 6, and a second glass substrate 41 over the glass electrode 6. The piezoelectric PVDF layers 4 and 40 are poled in opposite directions during formation so that when an electric field is applied, one layer expands while the other contracts. An alternative structure is shown in Figure 5. A central glass substrate 50 carries on one face two oppositely-poled layers 51 and 52 of PVDF, with an overlying layer 53 of photoconductor. On the other face of the glass substrate

50 are two unpoled layers 54 and 55 of PVDF and a further layer 56 of photoconductor. An electrode layer 57 is placed between the active PVDF layer 51 and the glass substrate 50, while another electrode 58, which is at least semi-transparent, is placed on the outside of the photoconductive layer 53. In the balanced structures shown in Figures 4 and 5, an expansion mismatch on one side is countered by an equal and opposite mismatch on the other side. A problem with such structures, however, is that sensitivity and spatial resolution can be reduced.

An alternative to a balanced structure in overcoming the problem of differing thermal expansion coefficients is one where the expansion coefficients of the layers have been matched. Thus, as shown in Figure 6, instead of the glass layer included in the mirror shown in Figure 1, a metal layer 60 is used as the rigid reflective layer. The piezoelectric and photoconductive layers are also modified to have expansion coefficients close to that of the metal.

Figure 7 illustrates another alternative structure, in which a thick and rigid layer 70 of the piezoelectric polymer is solvent cast with high surface quality to act as the reflective layer. The coefficients of the two polymers are then matched to each other to overcome the problem of differential expansion.

CLAIMS

1. An optical correction apparatus comprising, in combination,

(a) a light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezo-electric layers, and

(b) projection means for applying to the first surface thereof a light pattern adapted to produce the desired deformation of the mirror.

2. An apparatus according to Claim 1, wherein the piezoelectric layer comprises a polymeric material.

3. An apparatus according to Claim 2, wherein the polymeric material is poly(vinylidene fluoride).

4. An apparatus according to Claim 1, 2 or 3, wherein the photoconductive layer is a layer of amorphous silicon.

5. An apparatus according to Claim 1, 2 or 3, wherein the photoconductive layer comprises a polymeric material.

6. An apparatus according to Claim 5, wherein the polymeric material is poly(vinyl carbazole) doped with trinitro fluorenone.

7. An apparatus according to any preceding claim, wherein the reflective layer is a metal layer.

8. An apparatus according to Claim 7, wherein the reflective layer is a layer of aluminium.

9. An apparatus according to any preceding claim, wherein a glass support is provided between the piezoelectric layer and the reflective layer.

10. An apparatus according to Claim 9, comprising a second piezoelectric layer located on the first surface of the photoconductive layer, and a second glass support located on the second piezoelectric layer, the two piezoelectric layers being such that, under the action of an applied electric field, one piezoelectric layer expands while the other contracts.

11. An apparatus according to Claim 7 or 8, wherein the reflective layer is adapted to provide a support for the structure.

12. An apparatus according to any of Claims 1 to 8, comprising rigid mounting means holding the periphery of the layers.

13. An apparatus according to Claim 9, comprising a second piezoelectric layer located on the first piezoelectric layer, the layers having their molecules aligned substantially in opposite directions, and wherein the opposite face of the glass support is provided with two piezoelectric layers whose molecules are substantially unaligned, and an overlying photoconductive layer.

14. An apparatus according to any preceding claim, wherein the means for applying an electric field comprises transparent electrode layers.

15. An apparatus according to any preceding claim, wherein the projection means comprise a light source and a mask between the light source and the first surface.

16. An apparatus according to Claim 15, comprising at least one additional projection means having a different mask, and combining means for combining the output from all the projection means.

17. An apparatus according to Claim 16, comprising means for individually controlling the intensity of the light emitted by each projection means.

18. An apparatus according to any preceding claim, wherein the or each projection means comprises a laser diode.

19. An optical correction apparatus, substantially as described with reference to the drawings.

20. An optical system, including an optical correction apparatus according to any preceding claim, and means for measuring a characteristic of the light passing through the optical system and for controlling the output of the projection means in accordance therewith.

21. A light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer

overlying the piezoelectric layer, means for applying an electric field across the photoconductive and piezoelectric layers, a glass support between the piezoelectric layer and the reflective layer, a second piezoelectric layer located on the first surface of the photoconductive layer, and a second glass support located on the second piezoelectric layer, the two piezoelectric layers being such that, under the action of an applied electric field, one piezoelectric layer expands while the other contracts.

22. A light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, wherein a glass support is provided between the piezoelectric layer and the reflective layer, and a second piezoelectric layer located on the first piezoelectric layer, the layers having their molecules aligned substantially in opposite directions, wherein the opposite face of the glass support is provided with two piezoelectric layers, whose molecules are substantially unaligned, and an overlying photoconductive layer.

23. A light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical

contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, means for applying an electric field across the photoconductive and piezoelectric layers, and rigid mounting means holding the periphery of the layers such that the layers are supported solely thereby.

24. A light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a polymeric piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezoelectric layers, wherein the light-reflective layer is a layer of the same material as the piezoelectric layer and serves as a substrate for the layers.

25. A light-modulatable deformable mirror, comprising a photoconductive layer having a first surface for receiving a modulating light pattern and a second surface in electrical contact with a piezoelectric layer, a light-reflective layer overlying the piezoelectric layer, and means for applying an electric field across the photoconductive and piezo-electric layers, wherein the light-reflective layer is a metal layer serving as a substrate for the mirror.

26. A light-modulatable deformable mirror, substantially as described with reference to Figures 4 and 5 of the drawings.

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